The Spatial Stability of Rayleigh Wave Amplitudes and Path Dependent Propagation Characteristics of Central Asia

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Abstract

We analyzed Rayleigh waves from eleven regional events with pure continental paths recorded by the Kyrghystan broadband network (KNET) located in the northern Tien Shan mountains of central Asia. We utilized the frequency variable filter technique to isolate fundamental mode Rayleigh waves and extract stable surface wave amplitude spectra in the 10-40 s period band. We found a strong azimuthal dependence in the amount of variability of observed amplitudes across the 150 km aperture of KNET. Rayleigh waves from northerly azimuths that have propagated across the Kazakh shield show little difference in amplitudes. At the opposite extreme are Rayleigh waves from nuclear tests at Lop Nor which propagate across KNET from east to west. Lop Nor amplitude spectra vary by approximately a factor of 8 in the 10 to 30 s period band. Other paths generally show small variation in amplitude at periods above 20 s, but variation comparable to the Lop Nor path at periods less than 20 s. We also utilized KNET as an array to construct a suite of beams. We then used the frequency variable filter to extract amplitude spectra from the beam signals as we did for the single station data. Comparison of the results demonstrates that amplitude spectra variability correlates directly with stacking coherence. As a result, the performance of KNET as a long-period array for analyzing Rayleigh waves is highly dependent on azimuth. Events to the north and west can be expected to be stacked reliably to 10 s period or possibly less, while events to the east and south can not be stacked reliably for periods shorter than 20 s. We argue that our observations are explained by radical differences in the Rayleigh wave scattering properties of the crust in the tectonically active region to the south and east compared to the more stable crust of to the north and west. (Keywords: Rayleigh waves, magnitude, discrimination, Asia)

Objectives

We are working to utilize data from broadband, three-component seismic arrays to improve estimates of surface-wave magnitudes from small events observed at regional distances. This work is highly relevant since the M_s-m_b discriminant remains the most robust discrimination technique. However, this discriminant is known to not work as well for low yield explosions for reasons that are not fully understood. Our long-term goal is to understand why this happens and what alternative methods might be designed to provide more robust discriminates for small magnitude events. The focus of this paper is improved understanding of how surface waves propagate in the real earth. Our approach here is largely observational. We have utilized array processing in conjunction with state-of-the-art signal processing methods to examine the stability of observed spectral amplitudes of Rayleigh waves recorded by a broadband seismic array. The results provide new insights into surface wave propagation along pure continental paths.

Research Accomplished

Data

For this study we have utilized data from the IRIS Joint Seismic Program broadband array in Kyrghystan, which we will refer to as KNET (Figure 1). KNET is a ten element array that began operation in the summer of 1991 and remains operational as of the date of this report. The aperture of this array is approximately 150 km with nominal station spacings of 20-30 km. It is equipped with STS-2 broadband sensors and utilizes digital telemetry to provide a dynamic range of 120 dB. The system also records two separate data streams: (1) a 100 sps triggered mode using a network trigger algorithm; and (2) 20 sps continuous recording. Most of this work is based on signals extracted from the 20 sps stream because the 100 sps records commonly turn off before or during

Date(D/M/Y)	Julian Day	Origin Time	Latitude	Longitude	Depth (km)	m_b	Region
22/9/1991	265	06:32:37.3	49.64N	156.55E	30	5.5	Kuril Island
27/10/1991	300	07:01:23.2	40.19N	63.05E	39	5.0	Uzbekistan
08/11/1991	312	15:13:43.8	26.28N	70.58E	22	5.6	India-Pakistan
26/11/1991	330	19:40:48.5	42.05N	142.52E	56	6.1	Japan
24/4/1992	115	07:07:23.9	27.55N	66.07E	25	5.9	Pakistan
21/5/1992	142	04:59:57.5	41.60N	88.81E	0	6.5	Lop Nor
27/6/1992	179	13:21:20.9	35.14N	81.13E	33	5.0	s.XinJiang, China
11/27/1992	332	21:09:16.67	37.47N	59.86E	24	5.1	Turkmenistan
5/10/1993	278	01:59:56.2	41.65N	88.68E	0	5.9	Lop Nor
7/10/1994	280	03:25:58	41.55N	89.07E	0	5.9	Lop Nor
15/5/1995	135	04:05:57.9	41.59N	88.74E	0	6.1	Lop Nor

Table 1. Source parameters of events used in this study.

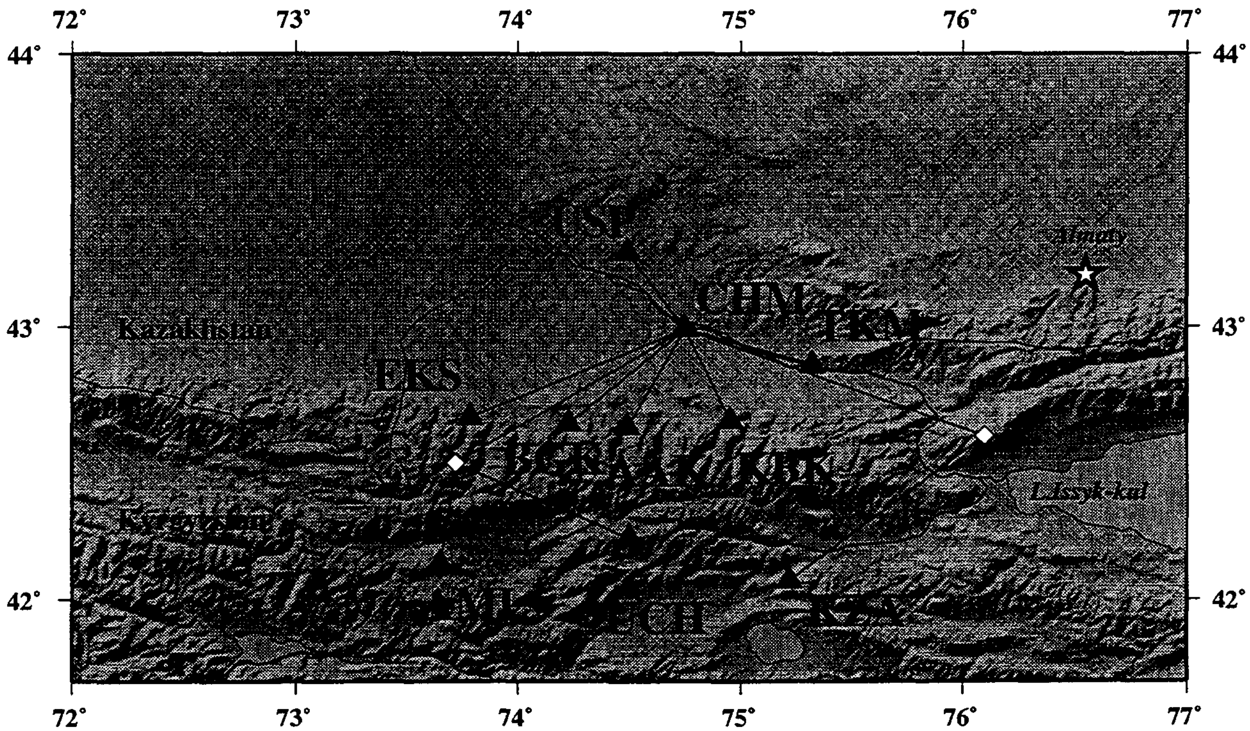

Figure 1. Map of KNET broadband array. Triangles are station locations. Diamonds are radio repeater sites and lines illustrate radio transmission links. Background is a shaded relief map of topography. Location of this array in central Asia is illustrated in Figure 2.

the surface wave arrivals.

To date we have fully studied Rayleigh wave data from eleven events whose source parameters are given in Table 1. This data set consists of seven earthquakes and four nuclear explosions from the Chinese test site at Lop Nor. These events were selected from the larger data set based on three major criteria:

(1) We looked at all available data from nuclear explosions.

(2) Earthquakes were selected to span as wide a range of azimuths as feasible.

(3) We considered only pure continental paths. The Kuril Island and Japan events (Figure 2) actually propagate across a back-arc basin, but because the back-arc is near the source and only a small fraction of the path we consider these "pure" to all intents and purposes.

(4) We focused on events at regional distances (5 to 20 degrees). For more northerly azimuth, however, we were forced to use more distant events (Figure 2).

The distribution of paths we have been able to study with available data recorded by KNET are shown in Figure 2. Notice that there is a gap in azimuth of approach of nearly 180 degrees to the north and west of KNET. We may be able to eventually fill the gap to the west with events from the Aegean, but significant events with pure continental paths from the north are unlikely unless Russia resumes nuclear testing.

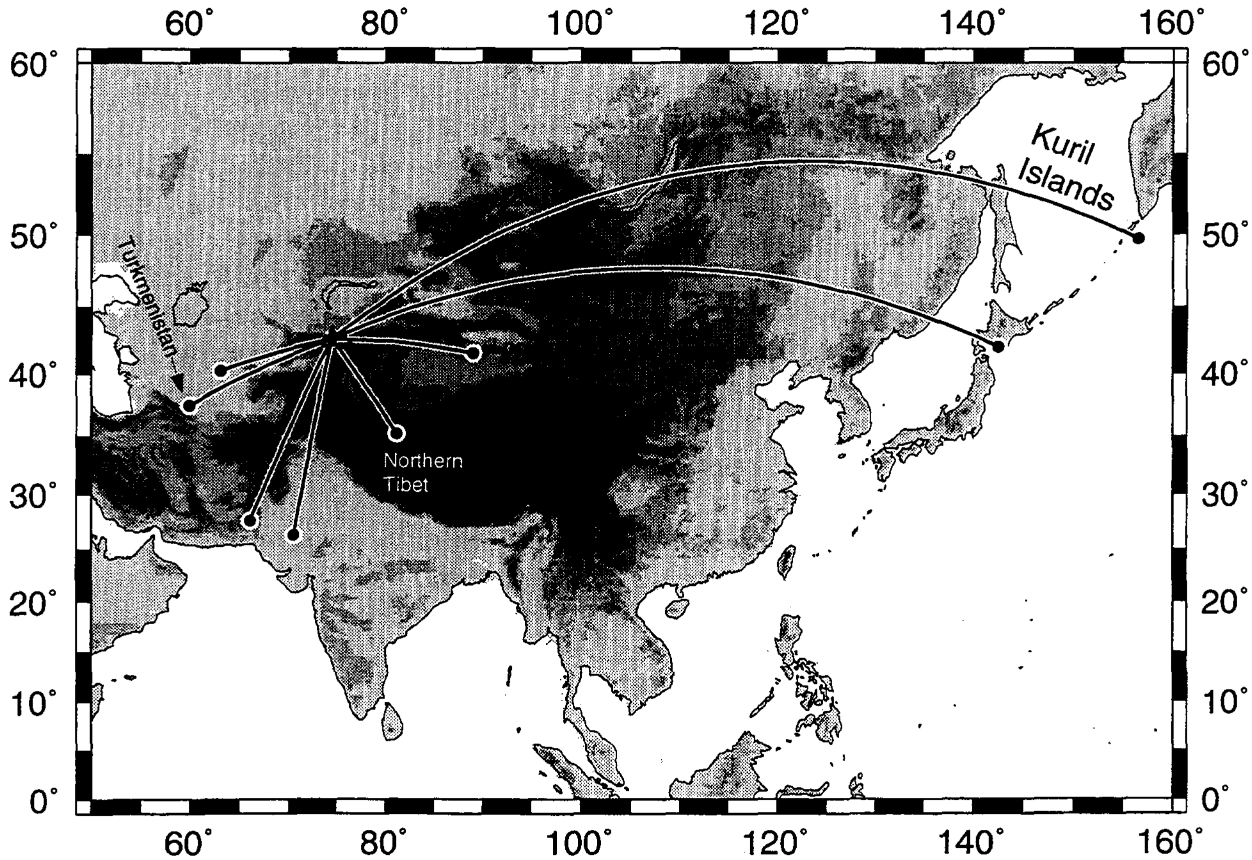

Figure 2. Map showing great circle paths of surface waves analyzed in this study. Black circles mark locations of each source. All events were recorded by the broadband network (KNET) in Kyrghystan. Background is grey scale topography with elevations over 5000 m black. Events for which results are presented in Figure 3 are labelled.

Methods

We are utilizing a mix of single station surface wave and array processing techniques. The array processing we used is one of the simplest methods possible. We use KNET as a long-period array, and compute a series of simple slant-stack array beams. In a recently completed paper (Pavlis and Mahdi, 1995) we conducted a more comprehensive array analysis of three regional events recorded by KNET. We found strong evidence for extensive multipathing and scattering along two of the three paths. Multipathing and scattering have an affect on array processing of surface waves that is somewhat different than a nondispersive signal like a P wave. In array processing of impulse signals, it is common practice to construct a "best beam" defined by f-k analysis. That is, f-k analysis is used to define the stacking velocity and back azimuth that will yield the maximum power in the beam. The resulting velocity and back azimuth are then used to define the "best beam" for that phase. In the presence of multipathing and scattering, the "best beam" for a surface wave become an ill defined quantity. The reason is that the "best beam" is frequency dependent because the dominate energy at one period may have a significantly different azimuth and velocity than the "best beam" at a different period. One could, in principle, process a range of beams that span the range of feasible "best beams". However, to make this manageable we limited our analysis to beams directed along the great circle path back azimuth and a fixed set of stacking velocities: 3.3, 3.5. 3.7, and 4.0 km/s. We made this choice for two reasons. First, it is the simplest model. Secondly, in our previous work (Pavlis and Mahdi, 1995) we found that the earliest parts of the surface wave packet was always the most coherent part of the surface wave group. This is consistent with what is expected from the geometry of forward scattering. That is, the initial surface wave arrival is a least time path, and as one moves later into the group the seismogram is the superposition of an ever expanding range of potential scattering points. One alternative we considered was to use the back azimuth obtained by f-k analysis of the front end of the Rayleigh wave signal as the "best beam" direction. However, up time for several KNET stations was marginal for the first two years of operation because of power and telemetry problems. As a result, reliable f-k azimuth estimates from a large fraction of the available data are not feasible. Thus, for consistency we decided it was preferable to use only the great circle path back azimuth.

For surface wave processing our goal is to extract the best possible estimate of the fundamental mode Rayleigh wave from a given signal. In our case this "signal" is either the seismogram recorded by a single station or an array beam. To accomplish this we used two basic tools. The first is an implementation of the multiple filter technique (MFT) of Dziewonski *et al.* (1969) by Herrmann (1973). We used the MFT to produce initial estimates of the dispersion curve and amplitude spectra of the fundamental mode signal.

Herrin and Goforth (1977) pioneered the use of phase-match filters (PMF) to isolate a mode of interest from a group of superimposed, multimode surface waves and to refine group and phase velocity measurements. They defined the phase-matched filter as a class of linear filters in which the Fourier phase spectrum of the filter is made equal to that of a given signal. This is done by removing the phase of the desired mode (In our case, we obtained this initial estimate from MFT analysis.) resulting in a zero-phase signal with energy concentrated about zero lag in the time domain. This dephased signal, which Russell *et al.* (1988) call a "pseudo-autocorrelation function", is windowed to isolate the mode of interest. When the effect of dispersion is restored, the resulting waveform is an estimate of the desired mode that reduces the effects of multipathing, other modes, and other forms of "noise". The principal enhancement introduced by Russell (1987) and Russell *et al.* (1988) was a more complex windowing scheme that combines the beneficial

aspects of Landisman *et al.*'s (1969) time variable filter with the PMF. This modified PMF method has been called the frequency variable filter. The principle advantage of the FVF is that it reduces the amplitude distortion (bias) of the PMF through the use of window functions that depend on frequency (Russell *et al.,* 1988). Because the focus of this study was on surface wave amplitude spectra, we used the FVF technique exclusively because of its superior capabilities in estimating amplitude spectra.

Results

Our major results are summarized in Figure 3. This figure displays estimates of fundamental mode Rayleigh wave amplitude spectra extracted by the FVF from four of the eleven events we have examined to date. The Lop Nor results presented are for the event on May 15, 1995. We present these four examples as representative of the larger data set. There are three important observational results that follow from figure 3 which we will now discuss.

1. There are dramatic variations in amplitude spectra of different stations within KNET and these variations are highly path dependent. The observed variations are of two flavors that need to be digested separately: (1) overall variability of the spectra from all the stations in the array viewed collectively; and (2) single station outliers like that from station AML in Figure 3d. First consider item 1. Notice that amplitude variability of the Kuril Islands event is almost negligible at all periods. Lop Nor is the opposite end member. There we find drastic variability of observed amplitudes at all periods. The other two events (ignoring for now the anomalous curve for AML) are intermediate. They tend to show quite large variability at periods shorter than about 20 s, but relatively small variations at longer periods. Results from the other events not presented in Figure 3 are consistent with this. That is, all Lop Nor explosions results show large amplitude variability, and results from similar azimuths are comparable. The Kuril Islands event shows the least variability of all the data.

Anomalous results like the spectrum for AML shown in Figure 3d are, we believe, a different issue. The result is particularly hard to explain because the observed amplitudes are anomalously low across the entire frequency band. We have similar examples of anomalous amplitude behavior of station CHM for two other events that are not shown in Figure 3. We are quite certain this is not an instrumentation problem for three reasons. First, high frequency signals do not show this anomalous behavior. Secondly, different stations show this anomalous type behavior for different events. Finally, gain codes are encoded in every transmitted packet and overall system responses are known very accurately. Pavlis and Mahdi (1995) demonstrated from particle motion analysis of the same event analyzed in Figure 3d that this anomalous amplitude is associated with a pronounced flattening of the Rayleigh wave elliptical particle motion. As a result we speculate that this type of anomalous amplitude response may result from a site effect related to 3-D structure of the crust and upper mantle beneath KNET at scale lengths less than a wavelength.

2. There is a general tendency for amplitude fluctuations to increase below 20 s period.

3. At periods of 20 s and above FVF filtering of the array beam from KNET provides a reasonably stable estimate of average amplitude of the single station measurements. Figure 3d shows that this remains true even in the presence of a relatively severe outlier like AML. Furthermore, this is relatively true even for the wildly variable results from Lop Nor. Below 20 s period there is a strong tendency for the beam to systematically underestimate the amplitude. This bias scales with the degree of amplitude fluctuation across the array. That is, for events like the Kuril Island event or the Turkmenistan event (ignoring AML) the amplitude bias is relatively small

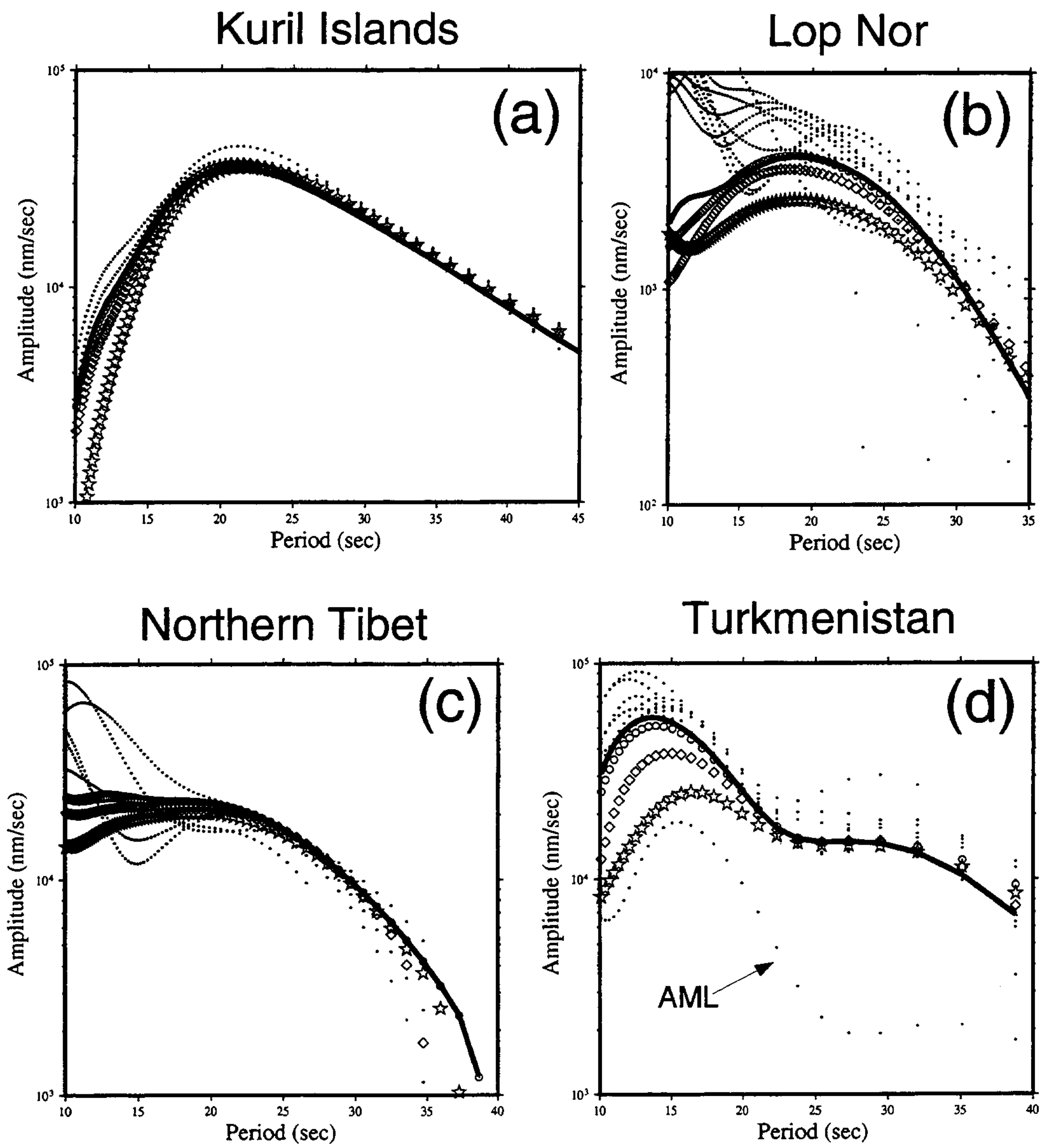

Figure 3. Amplitude versus period variations for different KNET stations and array beams. Results are presented here for four of the eight paths shown in Figure 2. Amplitudes spectra shown were, in all cases, obtained from the estimates produced by the frequency variable filter method of Russell *et. al* (1988). Dots show results from individual stations. Others are for different array beams constructed, in all cases, by pointing the array at the source back azimuth and stacking over different phase velocities. Stars are result using a velocity of 4.0 km/s; diamonds using 3.7 km/s; open circles used 3.5 km/s; and the solid line used 3.3 km/s.

while for Lop Nor the beam amplitude is more an order of magnitude smaller at 10 s periods.

To understand these three basic observations it is important to first grasp an issue of scale. The aperture of KNET is approximately 150 km. This means that for the range of periods analyzed in Figure 3, KNET spans a range of from around 1 to 5 wavelengths. This is why KNET is a functional long-period array for surface-waves in the band shown in Figure 3. It is well known that seismic arrays have difficulty yielding coherent stacks when the aperture of the array exceeds from 2 to 5 wavelengths. The loss of amplitude in the beam at periods less than about 20 s is a direct consequence of this. That is, at these shorter periods the signals do not stack. This is not a consequence of choosing the incorrect beam azimuth and slowness. Pavlis and Mahdi (1995) conducted moving window broadband f-k analysis on the October 1994 Lop Nor and the Turkmenistan events shown in Figure 3b. We found that for the Lop Nor path these shorter periods would not yield a coherent stack from any direction, while we could produce reasonable stacks at these periods for the Turkmenistan event. Thus, there is a strong azimuthal variation in the stacking capabilities of this array. For some azimuths (Figure 3a and 3d) KNET is a reasonable surface wave array for periods as short as 10 s, while for others (Lop Nor) is doesn't even work very well at 30 s period.

We would argue that these results are well explained by known large scale crustal structure of central Asia. The Kuril Islands path (Figure 2) traverses a stable shield region for all but the beginning and ending sections of the path. The lack of scattering along this path translates into almost negligible amplitude variations across the array. Paths from the southwest (Figure 3d) are relatively simple because these waves propagate primarily through a single crustal block which Zonenshain *et al.* (1990) call the Kara Kum-Tarim block and Sengor (1984) calls the Cimmerian subcontinent. This section of the crust seems to have been accretted onto Asia during the late Paleozoic, and forms the basement in an east-west band along the southern boundary of the former Soviet Union and into China in the Tarim basin (the almond shaped flat region within which the Lop Nor test site is located). This crustal block is relatively undeformed to the southwest. This appears to translate into relatively simple crustal structure and minimal scattering of 10-40 s Rayleigh waves. Surface waves from sources to the south and east of KNET, on the other hand, are strongly contaminated by extensive scattering and mulitpathing due to interaction with the complex geologic structures that characterize the crust in that region (Figure 2). An interesting preliminary observation is that propagation from the east (Lop Nor) is subject to greater amplitude fluctuations and inferred scattering than propagation from more southerly azimuths (e.g. Figure 3c). This may relate to the fact that the overall crustal fabric of this area of central Asia has a predominant east-west strike due to the predominant north-south compression that has thrown up the Tien Shan mountains.

A final result we note is that these results confirm an assertion we made previously (Pavlis and Mahdi, 1995) that in stacking surface wave data from an array like KNET, it is preferable to tune the beam to the highest frequency of interest. In all cases except Lop Nor the results are essentially identical for the full range of stacking velocities we used at periods longer than about 20 s. This occurs because the phasing errors induced by an inappropriate phase velocity have a negligible impact at the longer periods. Thus the best overall results are obtain by using the slowest phase velocity, which is appropriate for the shortest periods.

Conclusions and Recommendations

Regional earthquake monitoring networks equipped with broadband sensors and modern digital recording systems can double as highly functional long-period arrays. It is apparent to us

that regional earthquake monitoring networks throughout the world will evolve to this level of technology in the future. We assert that regional networks with this level of technology can play a critical role in the future in monitoring a CTBT by providing auxiliary data to discriminate questionable events. We recommend that CTBT negotiations should give careful consideration to the potential role of upgraded regional networks as a global monitoring resource.

Our work demonstrates that networks like KNET are highly useful tools for stacking data to obtain more reliable estimates of M_s than what would be possible with a single broadband station. On the other hand, we see that a network like KNET, which is located in an active tectonic zone defined by a major mountain belt, has highly variable utility in stacking surface waves. Our current working hypothesis to explain the observed differences in amplitude and frequency dependent stacking capabilities for the array is that we are seeing the interference effects of distinct multipaths and/or pervasive scattering of surface waves that characterize complex paths like that from Lop Nor into KNET.

Finally, we claim our work demonstrates although 20 s Rayleigh waves are the backbone of the most robust discrimination method presently known, there is a considerable lack of knowledge on the basic mode by which these waves propagate. The amplitude variations and stacking characteristics we observe are not consistent with layered earth structures commonly used to model this kind of data. Additional careful analysis of surface waves using arrays of three-component, broadband sensors will be necessary to fully understand the phenomena we have observed here.

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